Methods for detecting the 3D percolation of photons in the early universe.

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Reionization

LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

Jean-François Podevin (illustration), Steven Furlanetto, Aaron Slosar and Lars Hernquist Harvard University (simulations)
The Epoch of Reionization

Figure 13.

A slice along the frequency direction for the neutral fractions of hydrogen in the IGM. The repetition along the frequency direction marks a break redshift, $z = 6$. The color bar represents the mass density of stars formed in a box at a cosmic time of $13$ Gyr. This mass in stars is then distributed among the halos according to the mass of the halo as, $ho_\text{halo} = \dot{\rho}_\star \approx 10^{-3} M_\odot h^{-1} \text{yr}^{-1} \text{Mpc}^{-3}$, which is the case in our model. Notice that this approximation is valid only if the typical lifetime of stars is much smaller than the total mass density of stars formed in the box, $\rho_\star (z = 0) / \rho_\text{halo}$. This ensures that copious amounts of photons from early galaxies is assumed to be 10%.

In the above model, we have assumed that the spectral energy distribution (SED) of the quasar extends well above the ionization energy of hydrogen. This ensures that copious amounts of photons are available to ionize the hydrogen in the IGM while at the same time reducing the number of hard X-ray photons that could potentially ionize hydrogen.

Using the models of ionizing sources and the algorithm to generate light elements we have developed (details in the text, section 5), quasars are far more efficient at ionizing the IGM earlier than stars. This is mainly due to the efficiency (power-law) of quasars on the ionization process. They manage to ionize the IGM much earlier than stars, because we assume 100 solar mass stars as the source that have a lifetime, $\delta t = 3 \times 10^7$ yr, which is the case in our model. The escape fractions of ionizing photons from early galaxies is assumed to be 10%.

5.3 Statistical differences in the history of reionization

Using the models of ionizing sources and the algorithm to generate light elements we have developed (details in the text, section 5), quasars are far more efficient at ionizing the IGM earlier than stars. This is mainly due to the efficiency of quasars on the ionization process. They manage to ionize the IGM much earlier than stars because we assume 100 solar mass stars as the source that have a lifetime, $\delta t = 3 \times 10^7$ yr, which is the case in our model. The escape fractions of ionizing photons from early galaxies is assumed to be 10%.

5.2 Prescription for the cutoff in the SED at the higher and lower end of the energies.

The Epoch of Reionization

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Movies of simulations

M. Alvarez  http://www.youtube.com/watch?v=dgXfTx2e2MA
ESO  http://www.youtube.com/watch?v=6L1N95iRG8l
Noisy Images

• Typical amplitude: 10-30mK

• Typical noise after deep imaging: 10-30mK

• Statistical detection regime

• Foregrounds are 1000s of K

Zaroubi et al 2012
The Murchison Widefield Array (MWA, http://www.mwatelescope.org) and the Precision Array for Probing the Epoch of Reionization (PAPER, http://eor.berkeley.edu)
Statistical detection

- Power spectrum
- Weiner filtering
- pdf/difference pdf
- bispectrum
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Techniques in Literature

- Power Spectrum
- pdf
- bispectrum
- Image filtering

Imaging Required
Interferometry and the Power Spectrum
interferometry measures in Fourier Space

Instrument Frame  Power Spectrum

Morales and Hewitt 2004
Foregrounds have smooth spectra

- Foregrounds are spectrally smooth - reionization is not.

- Much of the foreground is point sources. Which can be simply modeled.

Dillon et al 2013
Response to Point Sources

\[ V_{ij} \approx \sum_s S_s e^{-2\pi i d_{s} \nu} + \int I(\hat{s}, \nu) e^{-2\pi i \hat{s} \cdot \bar{\nu} / c} d\Omega \]

Point Sources (wide band) \hspace{1cm} EoR (Narrow band)
delay spectrum

• The interferometer response to point sources

\[ V_{ij} \approx \sum_{s} S_s S^{-2\pi id_s \nu} . \]

Point Sources (wide band)

• Is a delta function in the third power spectrum dimension

\[ \tilde{V}_{ij} = S \delta(\eta - \hat{s} \cdot \hat{b} / c) \]

\[ d = \hat{s} \cdot \hat{b} / c \]

Beam
Averaging over many many sources

- Sources limited by primary beam, and ultimately by the horizon
- maximum delay increases with length of baseline.
Another Perspective

- Each baseline samples the fourier plane.

- Distance from the center of the plane increases radially
Another Perspective

- Each baseline samples the Fourier plane.
- Distance from the center of the plane increases radially.
- This is also the basic description of the Fourier Slice Theorem.
- Each delay transformed baseline spectrum is a projection slice of the sky.
# Summary of the Reionization Problem as compared to Medical Imaging

- **Separate the data into three components**
  - Foregrounds
  - Noise
  - a bubble and void-like structure

- **Medical Equivalent**
  - Construct a holographic model
  - High noise environment (like ambient field NMR)
  - anomolous structure
Summary

• wide bandwidth correlated spectroscopy of a 3D region

• filter a holographic model of the dominant signal

• Detect anomalous structure in a high noise environment

• NB: This holography is made possible by the linearity of ElectroMagnetism
Beyond linearity

- the delay transform uses linearity of EM to derive position information
- meta-materials allow the encoding of additional information.
- Scale up this single pixel feed. (20GHz, 40cm)

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- Meta-materials allow the selective encoding of additional information.

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  (@20GHz - 40cm)
  (@150MHz-60m)

- One PAPER row = 200m
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Some pictures (or The End)